

The Bridge Stabilized Oscillator *

By L. A. MEACHAM

A new type of constant frequency oscillator of very high stability is presented. The frequency controlling resonant element is used as one arm of a Wheatstone resistance bridge. Kept in balance automatically by a thermally controlled arm, this bridge provides constancy of output amplitude, purity of wave form, and stabilization against fluctuations in power supply or changes in circuit elements. A simple one-tube circuit has operated consistently with no short-time frequency variations greater than ± 2 parts in 10^6 . Convenient means are provided for making precision adjustments over a narrow range of frequencies to compensate for long-time aging effects.

Description of the circuit is followed by a brief linear analysis and an account of experimental results. Operating records are given for a 100 kc. oscillator.

INTRODUCTION

THE problem of improving the stability of constant frequency oscillators may be divided conveniently into two parts, one relating to the frequency controlling resonant element or circuit, and the other to the means for supplying energy to sustain oscillations. The ideal control element would be a high- Q electrical resonant circuit, or a mechanical resonator such as a tuning fork or crystal, whose properties were exactly constant, unaffected by atmospheric conditions, jar, amplitude of oscillation, age, or any other possible parameter. The ideal driving circuit would take full advantage of the resonator's constancy by causing it to oscillate at a stable amplitude and at a frequency determined completely by the resonator itself, regardless of power supply variations, aging of vacuum tubes or other circuit elements, or the changing of any other operating condition.

This paper, concerning itself principally with the second part of the problem, describes an oscillator circuit which attains a very close approximation to the latter objective. The "Bridge Stabilized Oscillator" provides both frequency and amplitude stabilization, and as it operates with no tube overloading, it has the added merit of delivering a very pure sinusoidal output.

OSCILLATOR CIRCUIT

The bridge stabilized oscillator circuit, shown schematically in Fig. 1, consists of an amplifier and a Wheatstone bridge. The amplifier out-

* Presented at Thirteenth Annual Convention of Institute of Radio Engineers, New York City, June 16, 1938. Published in *Proc. I. R. E.*, October 1938.

put is impressed across one of the diagonals of the bridge, and the unbalance potential, appearing across the conjugate diagonal, is applied to the amplifier input terminals. One of the four bridge arms, R_1 , is a thermally controlled resistance; two others, R_2 and R_3 , are fixed resistances, and the fourth, $Z_4 = R_4 + jX_4$, is the frequency-controlling resonant element.

In this discussion Z_4 is assumed to represent a crystal suitable for operation at its low-impedance or series resonance. A coil and condenser in series could be substituted, and even a parallel-resonant control element might be used by exchanging its position in the bridge

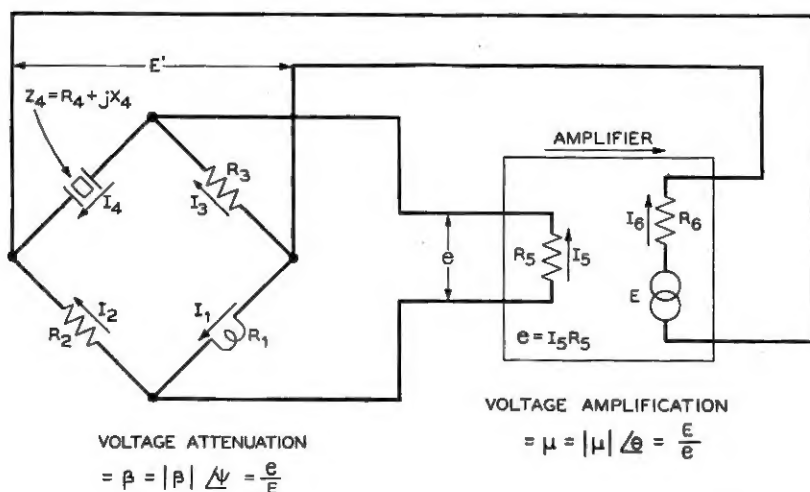


Fig. 1—Schematic circuit diagram of bridge stabilized oscillator.

with R_2 or R_3 . Operating a crystal at series resonance has the advantage of minimizing effects of stray capacitance.

The bridge is kept as nearly in exact balance as possible. Assuming that R_1 , R_2 and R_3 are pure resistances, we may write for exact reactive balance,

$$X_4 = 0,$$

and for exact resistive balance,

$$\frac{R_1}{R_2} = \frac{R_3}{R_4}.$$

In order that the circuit may oscillate, a slight unbalance is required. Accordingly R_1 must be given a value slightly smaller than $(R_2 R_3)/R_4$,

so that the attenuation through the bridge is just equal to the gain of the amplifier.

It is evident that if all the bridge arms had fixed values of resistance, the attenuation of the bridge would be very critical with slight changes in any arm. This would obviously be undesirable, for the circuit would either fail to oscillate, or else build up in amplitude until tube overloading occurred. The thermally controlled resistance R_1 eliminates this difficulty. This arm has a large positive temperature coefficient of resistance, and is so designed that the portion of the amplifier output which reaches it in the bridge circuit is great enough to raise its temperature and increase its resistance materially. A small tungsten-filament lamp of low wattage rating has been found suitable. It functions as follows:

When battery is first applied to the amplifier, the lamp R_1 is cold and its resistance is considerably smaller than the balance value. Thus the attenuation of the bridge is relatively small, and oscillation builds up rapidly. As the lamp filament warms, its resistance approaches the value for which the loss through the bridge equals the gain of the amplifier. If for some reason R_1 acquires too large a resistance, the unbalance potential e becomes too small or possibly even inverted in phase, so that the amplitude decreases until the proper equilibrium is reached.

This automatic adjustment stabilizes the amplitude, for the amount of power needed to give R_1 a value closely approaching $(R_2 R_3)/R_4$ is always very nearly the same. A change in the amplifier gain would cause a readjustment of the bridge balance, but the resulting variation in R_1 or in the amplifier output would be extremely small. The operating temperature of the lamp filament is made high enough so that variations in the ambient temperature do not affect the adjustment appreciably.

No overloading occurs in the amplifier, which operates on a strictly Class A basis, nor is any non-linearity necessary in the system other than the thermal non-linearity of R_1 . As the lamp resistance does not vary appreciably during a high-frequency cycle, it is not a source of harmonics (or of their intermodulation, which Llewellyn¹ has shown to be one of the factors contributing to frequency instability).

In contrast to the lamp, an ordinary non-linear resistance, of copper oxide for example, would not be suitable for R_1 . A resistance of the thermally-controlled type having a negative temperature coefficient

¹ "Constant Frequency Oscillators," F. B. Llewellyn, *Proc. I. R. E.*, December 1931.

could be used by merely exchanging its position in the bridge with R_2 or R_3 .

The frequency control exerted by the crystal depends upon the fact that the phase shift of the amplifier must be equal and opposite to that through the bridge. In the notation of Black,² applied to the circuit of Fig. 1,

$$\mu = \frac{E}{e} = |\mu| \angle \theta,$$

and

$$\beta = \frac{e}{E} = |\beta| \angle \psi.$$

The condition for oscillation is

$$\mu\beta = 1 \angle 0,$$

which implies that $|\mu\beta| = 1$ and $\theta = -\psi$.

The vector diagrams of Fig. 2 illustrate the frequency-stabilizing action of the bridge by showing the voltage relations therein for two values of amplifier phase shift, θ . When θ is zero, as in diagram A, the unbalance vector e is in phase with the generated voltage E applied to the bridge input, and thus all the vectors shown are parallel. They are displaced vertically from each other merely to clarify the drawing. The crystal is here constrained to operate at exact resonance.

In diagram B, the amplifier is assumed to have changed its phase for some reason by an amount far in excess of what would be anticipated in practice, θ here having a value of $+45$ degrees. The important point to be observed is that the ratio of θ to the resulting change in the phase angle ϕ of the crystal impedance Z_4 is very large. That is, the crystal is still operating close to resonance in spite of the exaggerated change in the driving circuit. If the gain of the amplifier were greater, the action of the thermally controlled resistance would keep the amplifier output vector E practically the same in length, making the unbalance vector e correspondingly shorter. The angle ϕ would therefore have to be more acute for the same value of θ , and it follows that with increased gain the crystal is held closer to true resonance and the stability is improved.

When θ equals zero, changes in $|\mu|$ do not affect the crystal operating phase, but for any other small value of θ , gain variations cause slight readjustments of the angles between vectors. The amplifier should accordingly be designed for zero phase shift, and also, of course, should have as much phase stability as possible.

² "Stabilized Feedback Amplifiers," H. S. Black, *Bell System Technical Journal*, January 1934.

In this discussion the input and output impedances of the amplifier, R_5 and R_6 , are assumed to be constant pure resistances. Actually, changes in the tube parameters or in certain circuit elements are likely to affect both the magnitude and the phase of these impedances. It may be shown, however, that such changes have the same effect upon the bridge and upon the frequency as do changes of about the same

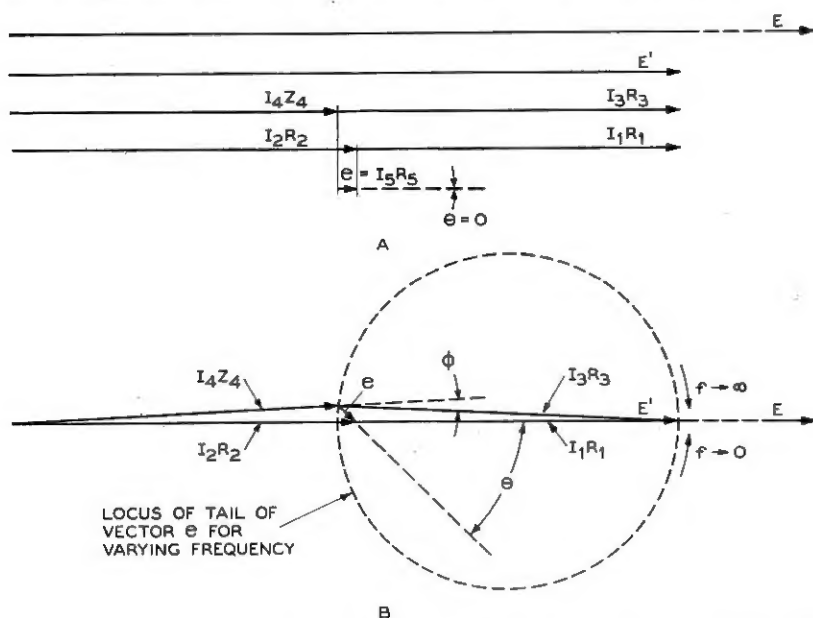


Fig. 2—Vector diagrams illustrating operation of bridge oscillator, with simplifying assumptions that R_5 is large and that E and E' are strictly in phase.

- A—At resonance
 $Z_4 = R_4 + j0$
 $\theta = 0$
 $R_1 < R_2 = R_3 = R_4$
 B—Above resonance
 $Z_4 = R_4 + jX_4$
 X_4 Inductive
 $\theta = +45^\circ$
 $R_1 < R_2 = R_3 = R_4 \ll R_5$

percentage in $|\mu|$ or θ ; therefore all variations in the driving circuit external to the bridge may be assumed for convenience to be represented by variations in its gain and phase.

This leniency with regard to R_5 and R_6 does not apply to the other bridge resistances, however. R_1 , R_2 and R_3 are directly responsible for the crystal's operating phase and amplitude; they should be made as stable and as free from stray reactance as possible.

The effect of the bridge upon harmonics of the oscillation frequency is of interest. Harmonics, being far from the resonant frequency of the crystal, are passed through the bridge with little attenuation but with a phase reversal approximating 180 degrees, as illustrated by the dotted locus in Fig. 2. Thus if the amplifier were designed to cover a band broad enough to include one or more harmonics and if care were taken to avoid singing at some unwanted frequency, a considerable amount of negative feedback could be applied to the suppression of the harmonics in question.

CIRCUIT ANALYSIS

In the following section, expressions are derived for the frequency of oscillation in terms of the gain and phase shift of the amplifier, the Q of the crystal, and values of the bridge resistances. It is assumed that the latter are constant and non-reactive, and therefore, as explained previously, that all sources of frequency fluctuations apart from changes in the crystal itself appear as variations in $|\mu|$ or θ . Because the bridge oscillator does not rely upon non-linearity in the ordinary sense to limit its amplitude, the analysis can be based reasonably on simple linear theory.

In the near vicinity of series resonance the crystal may be represented accurately by a resistance R_4 , inductance L and capacitance C , connected in series. The reactive component of the crystal's impedance is accordingly

$$X_4 = \omega L - \frac{1}{\omega C} = \frac{\omega^2 LC - 1}{\omega C}. \quad (1)$$

Solving for the frequency,

$$\begin{aligned} \omega &= \frac{X_4}{2L} + \sqrt{\left(\frac{X_4}{2L}\right)^2 + \frac{1}{LC}} \\ &= \frac{1}{\sqrt{LC}} \left[\frac{X_4}{2} \sqrt{\frac{C}{L}} + \sqrt{1 + \left(\frac{X_4}{2} \sqrt{\frac{C}{L}}\right)^2} \right] \\ &= \frac{1}{\sqrt{LC}} \left[1 + \frac{X_4}{2} \sqrt{\frac{C}{L}} + \frac{1}{2} \left(\frac{X_4}{2} \sqrt{\frac{C}{L}}\right)^2 \right. \\ &\quad \left. - \frac{1}{2} \cdot \frac{1}{4} \left(\frac{X_4}{2} \sqrt{\frac{C}{L}}\right)^4 + \dots \right]. \quad (2) \end{aligned}$$

Near series resonance, $(X_4/2) \sqrt{(C/L)} \ll 1$. We therefore disregard powers higher than the first in the series expansion above and obtain the close approximation,

$$\omega \doteq \frac{1}{\sqrt{LC}} \left[1 + \frac{X_4}{2} \sqrt{\frac{C}{L}} \right]. \quad (3)$$

The frequency deviation from resonance, expressed as a fraction of the resonant frequency f_0 , is thus

$$\frac{f - f_0}{f_0} = \frac{\omega - \omega_0}{\omega_0} = \frac{X_4}{2} \sqrt{\frac{C}{L}}, \quad (4)$$

and in the region of interest, where ωL and $1/\omega C$ are approximately equal,

$$\frac{f - f_0}{f_0} = \frac{X_4}{2\omega L} = \frac{X_4}{2QR_4}. \quad (5)$$

Considering now the bridge circuit, and applying well-known equations,³ we obtain

$$\beta = \frac{I_5 R_5}{E} = \frac{AR_4 - jBX_4}{MR_4 + jNX_4}, \quad (6)$$

in which

$$\left. \begin{aligned} A &= R_5(R_2R_3 - R_1R_4), \\ B &= R_1R_4R_5, \\ M &= (R_1 + R_2)(R_3R_4 + R_5R_6) + (R_3 + R_4)(R_1R_2 + R_5R_6) \\ &\quad + (R_5 + R_6)(R_1R_4 + R_2R_3) + R_5(R_1R_3 + R_2R_4) \\ &\quad + R_6(R_1R_2 + R_3R_4), \\ N &= R_4(R_1 + R_3 + R_6)(R_2 + R_6) + R_1R_4(R_3 + R_5). \end{aligned} \right\} \quad (7)$$

and

The condition for oscillation, as mentioned previously, is $\mu\beta = 1 \angle 0$. Putting $\mu = \mu_1 + j\mu_2$, we may write

$$(\mu_1 + j\mu_2) \left(\frac{AR_4 - jBX_4}{MR_4 + jNX_4} \right) = 1, \quad (8)$$

which gives the pair of equations

$$\mu_1 AR_4 + \mu_2 BX_4 - MR_4 = 0 \quad (9)$$

and

$$\mu_2 AR_4 - (\mu_1 B + N)X_4 = 0. \quad (10)$$

For the special case in which the amplifier phase shift is zero ($\mu_2 = 0$), these become

$$\mu_1 = \frac{M}{A} = |\mu| \quad (11)$$

and

$$X_4 = 0. \quad (12)$$

³ "Transmission Circuits for Telephonic Communication," K. S. Johnson, pp. 284-5. D. Van Nostrand Company.

The latter equation indicates that the frequency is then independent of changes in any of the circuit parameters except the crystal, which must operate exactly at resonance.

If the phase of μ differs only slightly from zero, so that μ_2 is very small, then it may be inferred from continuity considerations that the frequency is still very nearly independent of all circuit parameters, except of course variations in θ , the phase of μ . When θ is limited to values for which $\mu_2 B X_4 \ll \mu_1 A R_4$, (11) still applies closely. Substitution into (10) gives

$$X_4 \doteq \frac{MR_4}{B\mu_1 + N} \cdot \frac{\mu_2}{\mu_1} \doteq \frac{MR_4\theta}{B|\mu| + N}, \quad (13)$$

and finally from (5) and (13) we obtain the frequency deviation in the form

$$\frac{f - f_0}{f_0} \doteq \frac{M\theta}{2Q(B|\mu| + N)}. \quad (14)$$

As noted above, this expression applies accurately only when θ is small, as it should be in a well designed bridge oscillator.

The effect of variations in the amplifier may be examined by differentiating (14). For changes in θ only,

$$\left. \frac{df}{f_0} \right]_{\theta} \doteq \frac{M}{2Q(B|\mu| + N)} d\theta, \quad (15)$$

and for those of $|\mu|$,

$$\left. \frac{df}{f_0} \right]_{|\mu|} \doteq - \frac{BM\theta}{2Q(B|\mu| + N)^2} d|\mu|. \quad (16)$$

Equations (15) and (16) have been found to be closely in accord with experiment, although the differentiation is not rigorously allowable (B , M and N being only approximately constant).

In the special case where all the fixed bridge resistances (R_2 to R_6 inclusive) are equal, and $|\mu|$ is large enough so that R_1 has nearly the same value, (14), (15) and (16) reduce to the following:

$$\frac{f - f_0}{f_0} \doteq \frac{8\theta}{Q(|\mu| + 8)}, \quad (17)$$

$$\left. \frac{df}{f_0} \right]_{\theta} \doteq \frac{8}{Q(|\mu| + 8)} d\theta, \quad (18)$$

$$\left. \frac{df}{f_0} \right]_{|\mu|} \doteq - \frac{8\theta}{Q(|\mu| + 8)^2} d|\mu|. \quad (19)$$

These expressions show, as did the vector diagrams, that for optimum stability the amplifier phase shift should be made approximately zero, the crystal should have as large a value of Q (as low a decrement) as possible, and the amplifier should have high gain. Linearity in the amplifier is also desirable, to minimize the modulation effects described by Llewellyn.¹ When present, these effects appear as variations in $|\mu|$ and θ .

One of the significant differences between the bridge oscillator and other oscillator circuits is the fact that its frequency stability is roughly proportional to $|\mu|$. This relationship holds at least for amounts of gain that can be dealt with conveniently. Although increased gain is generally accompanied by larger variations in phase, the two are not necessarily proportional. For example, if greater stability were required for some precision application than could be achieved with a single-tube bridge oscillator, and if the constancy of the crystal itself warranted further circuit stabilization, it could be obtained by adding another stage. The phase fluctuations in the amplifier might possibly be doubled, but the value of $|\mu|$ would be multiplied by the amplification of the added tube, giving an overall improvement.

To illustrate the high order of stability provided by a bridge oscillator, let us consider a model composed of a single-tube amplifier and a bridge in which all the fixed resistances are made equal to that of the crystal. We will assume the crystal to have a reasonably high ⁴ Q of 100,000. The amplifier phase, let us say, is normally zero, but may possibly vary ± 0.1 radian (± 6 degrees), and the value of $|\mu|$, nominally 400, may change ± 10 per cent. From (18) and (19) we find

$$\left. \frac{\Delta f}{f_0} \right|_{\theta} = \pm \frac{(8)(0.1)}{(100,000)(360 + 8)} = \pm 2.17 \times 10^{-8},$$

and (when θ has its maximum value of 0.1 radian)

$$\left. \frac{\Delta f}{f_0} \right|_{|\mu|} = \pm \frac{(8)(0.1)(40)}{(100,000)(360 + 8)^2} = \pm 2.36 \times 10^{-9}.$$

This example represents the degree of stabilization against circuit fluctuations that can be obtained with a simple form of the oscillator operating under poorly controlled conditions. By stabilizing the power supply and other factors affecting $|\mu|$ and θ , and by increasing the gain, the frequency variations arising in the driving circuit may be made negligible compared to the variations found at present in the properties even of the best mounted crystals.

⁴ For crystals in vacuum, values of Q as great as 300,000 have been obtained.

EXPERIMENT

The circuit diagram of an experimental bridge stabilized oscillator is shown in Fig. 3, and its photograph in Fig. 4. The amplifier unit consists of a single high- μ tube V_1 with tuned input and output transformers T_1 and T_2 and the usual power supply and biasing arrangements. The crystal, mounted in the cylindrical container at the left end of the panel, is one having a very low temperature coefficient of frequency at ordinary ambient temperatures. In Fig. 4 it is shown without provisions for temperature control. A high Q is obtained by clamping the crystal firmly at the center of its aluminum-

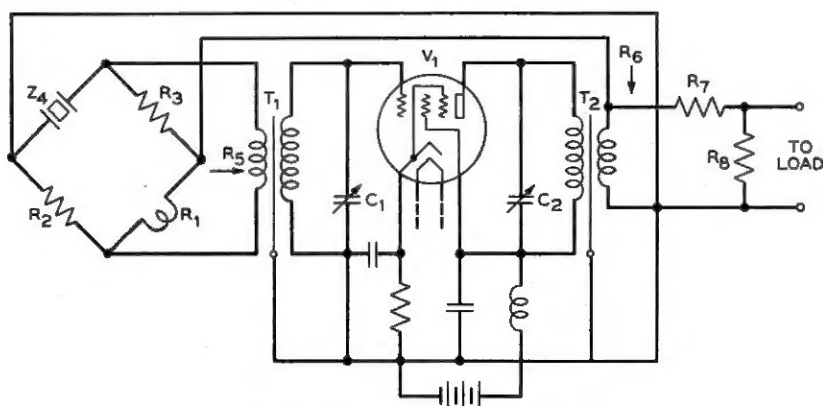


Fig. 3—Circuit of experimental bridge oscillator.

coated major faces between small metal electrodes ground to fit, and by evacuating the container.

Some of the circuit parameters are listed below:

R_1 = Tungsten-filament lamp,

R_2 = 100 ohms,

R_3 = 150 ohms,

Z_4 = 100 kc. crystal.

Characteristics at resonance:

R_4 = 114 ohms,

$X_L = X_C$ = 11,900,000 ohms,

Q = 104,000,

$R_5 = R_6$ = 150 ohms (approx.),

R_7 = 500 ohms,

R_8 = 200 ohms,

$|\mu|$ = 422 (52.5 db voltage gain from e to E).

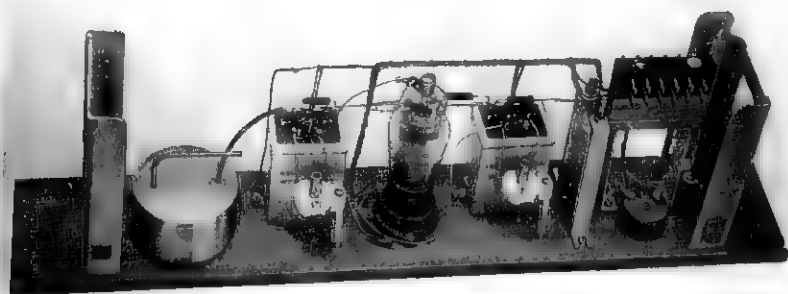


Fig. 4—Experimental bridge stabilized oscillator without provision for temperature control.

Figure 5 shows the resistance of the lamp R_1 plotted against the power dissipated in its filament. The large rise in resistance for small amounts of power is due to the effective thermal insulation provided by the vacuum surrounding the filament and to low heat loss by radiation. The lamp operates at temperatures below its glow point, assuring an extremely long life for the filament.

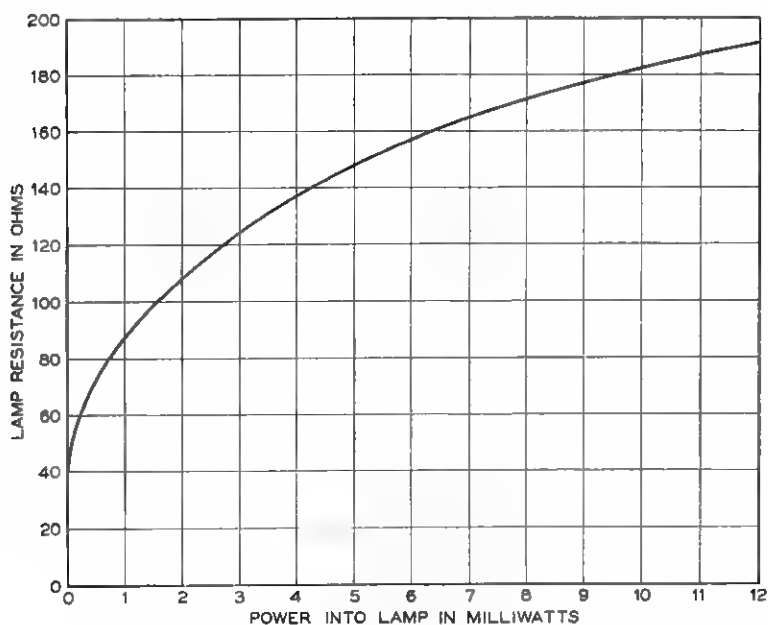


Fig. 5—Characteristic of lamp used for R_1 .

The particular value assumed by R_1 in the circuit of Fig. 3 is approximately $(R_2 R_3)/R_4 = [(100)(150)]/114 = 131.6$ ohms, and hence from Fig. 5 it follows that the power supplied to the lamp is about 3.7 milliwatts. The r.m.s. voltage across the lamp is computed to be 0.70 volt, and across the entire bridge, 1.23 volt. The power supplied to a load of 150 ohms through the pad composed of R_7 and R_8 is accordingly 0.22 milliwatt, or 6.6 *db* below 1 milliwatt, which is in agreement with measurements shown in Figs. 8 and 9, described below. These quantities are given to illustrate the fact that currents and voltages in

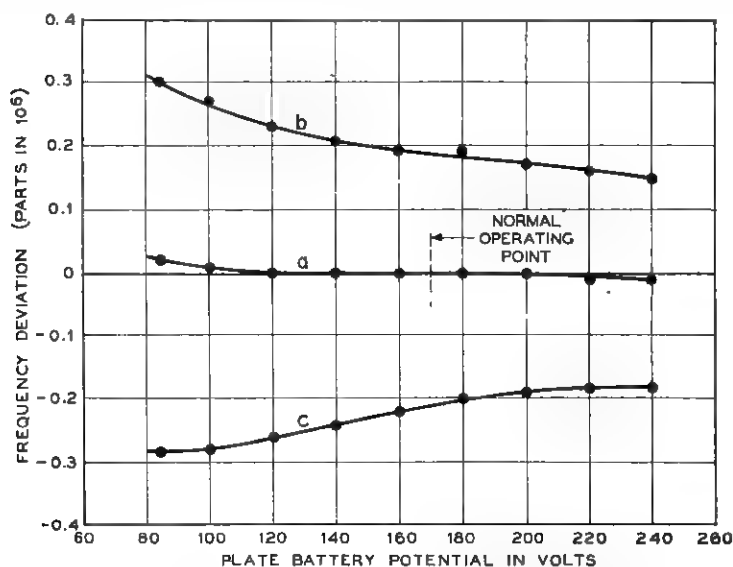


Fig. 6—Oscillator frequency vs. plate battery potential.

- a*— C_1 and C_2 tuned for maximum amplifier gain.
- b*— C_1 and C_2 decreased 5%.
- c*— C_1 and C_2 increased 5%.

this type of oscillator may be calculated readily from the values of the circuit elements, and without reference to the power supply voltages or the tube characteristics except to assume that they give the amplifier sufficient gain to operate the bridge near balance, and that tube overloading does not occur at the operating level.

Experimental performance curves for the circuit of Fig. 3 are presented in Figs. 6 to 11 inclusive. Figure 6 shows frequency deviation plotted against plate battery voltage for several settings of the grid and plate tuning condensers. For curve *a* the amplifier was adjusted at maximum gain, corresponding approximately to zero phase shift as

well. Here the frequency varied not more than one part in one hundred million for a voltage range from 120 to 240 volts. Curve *b* was taken with the two tuning capacitances C_1 and C_2 decreased 5 per cent from their optimum settings, and curve *c* with both capacitances increased 5 per cent. These detunings introduced phase shifts of about $\pm 40^\circ$ (± 0.70 radian), decreased $|\mu|$ by 0.8 *db* and changed the frequency, as shown in Fig. 6, approximately ± 2 parts in ten million. Although the analysis should not be expected to apply

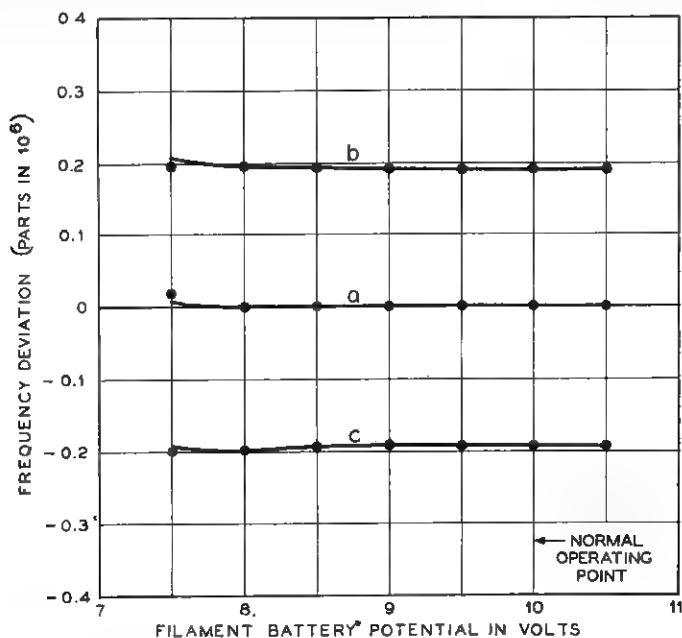


Fig. 7—Oscillator frequency vs. filament battery potential.

- a*— C_1 and C_2 tuned for maximum amplifier gain.
- b*— C_1 and C_2 decreased 5%.
- c*— C_1 and C_2 increased 5%.

accurately for such large phase shifts, calculation of the frequency deviations by means of (18) gives ± 1.4 parts in ten million—in fair agreement with the experimental results. As might be expected, curves *b* and *c* show somewhat less stability with battery voltage changes than does curve *a*.

Figure 7 presents a similar set of curves for variations of filament voltage. Here, for the "maximum-gain" tuning adjustment, a drop from 10 volts, the normal value, to 8 volts caused less than one part in one hundred million change of frequency, as shown in curve *a*.

In Fig. 8, the gain of the amplifier and the output level of the oscillator are plotted against plate battery voltage, while in Fig. 9 the same quantities are related to filament potential. These curves show that although power supply variations change the amplifier gain, they have but slight effect upon the amplitude of oscillation. This stabilization is produced, as explained heretofore, by the action of the lamp.

The oscillator was designed to work into a load of 150 ohms, its output impedance approximately matching this value. It might be expected that variations in the magnitude or phase angle of the load

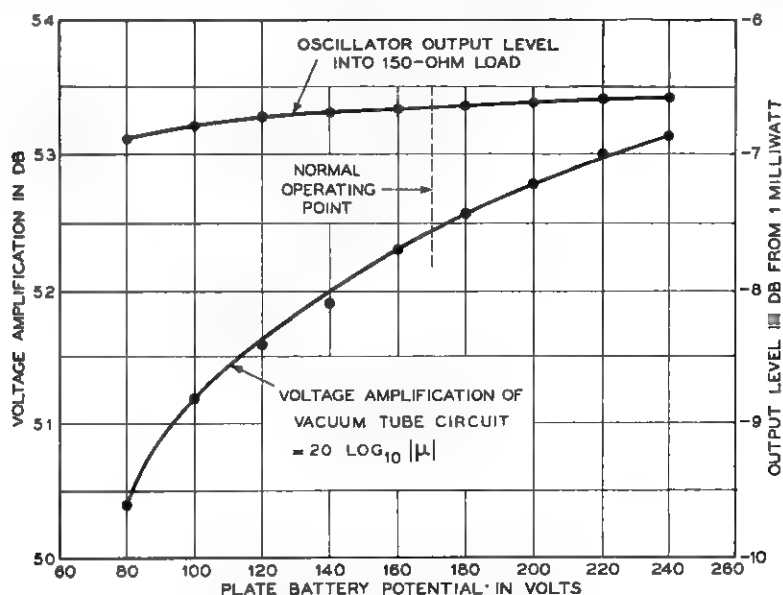


Fig. 8—Amplifier gain and oscillator output level vs. plate battery potential.

would affect the frequency materially even though a certain amount of isolation is provided by R_7 and R_8 . However, measurements made with (1) a series of load impedances having a constant absolute magnitude of 150 ohms but with phase angles varying between -90° and $+90^\circ$ and (2) a series of resistive loads varying between 30 ohms and open circuit, showed less than one part in a hundred million frequency variation. Graphs of these results have not been included, since they practically coincide with the axis of zero frequency deviation.

The tuned transformers T_1 and T_2 in this experimental model precluded the suppression of harmonics by negative feedback, $|\mu|$ being small at the harmonic frequencies. The tuning itself provided suppression, however, so that the measured levels of the second and third

harmonics in the output current were respectively 67 db and 80 db below that of the fundamental. This purity of wave form is of course largely dependent upon the absence of overloading.

To correct any small initial frequency error of the crystal and to allow for subsequent aging, a small reactance connected directly in series with the crystal provides a convenient means of adjusting the frequency as precisely as it is known. This added reactance may be considered as modifying either of the reactances in the equivalent series resonant circuit of the crystal. Figure 10 shows that for a small

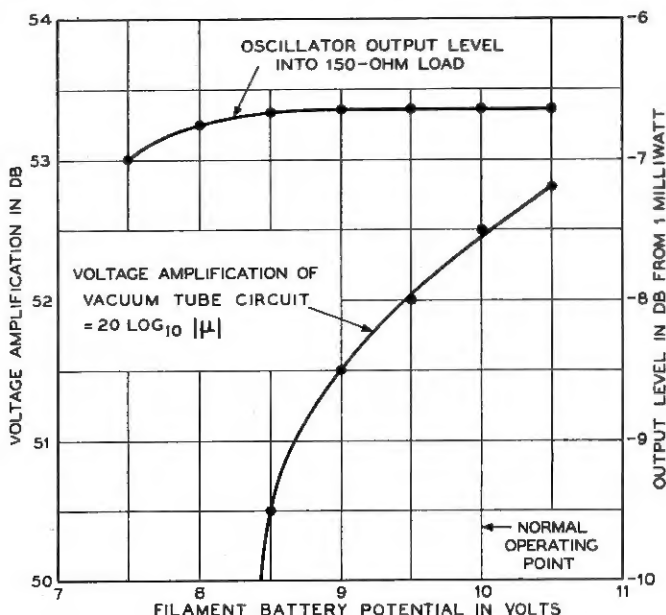


Fig. 9—Amplifier gain and oscillator output level vs. filament battery potential.

range of frequencies the change introduced in this manner is accurately proportional to the added reactance. Series inductance, of course, lowers the frequency, while series capacitance raises it. The stability requirement imposed on the adjusting reactance is only moderate, for its total effect upon the frequency should not be more than a few parts in a million.

The frequency measurements here presented were obtained using apparatus similar in principle to the frequency comparison equipment of the National Bureau of Standards.⁵ Frequency differences

⁵ "Harmonic Method of Intercomparing the Oscillators of the National Standard of Radio Frequency," E. G. Lapham, *Journal of Research of the National Bureau of Standards*, October 1936, p. 491.

between the oscillator under test and a reference bridge oscillator were read upon a linear scale calibrated directly in terms of frequency deviation. Full scale could be made one part in 10^4 , 10^5 , 10^6 or 10^7 by means of a simple switching operation. For most of the measurements in this paper the full-scale reading was one part in a million, and the resolution about ± 0.005 part in a million.

By using a recording meter with this measuring set, continuous frequency comparisons between two independent bridge oscillators

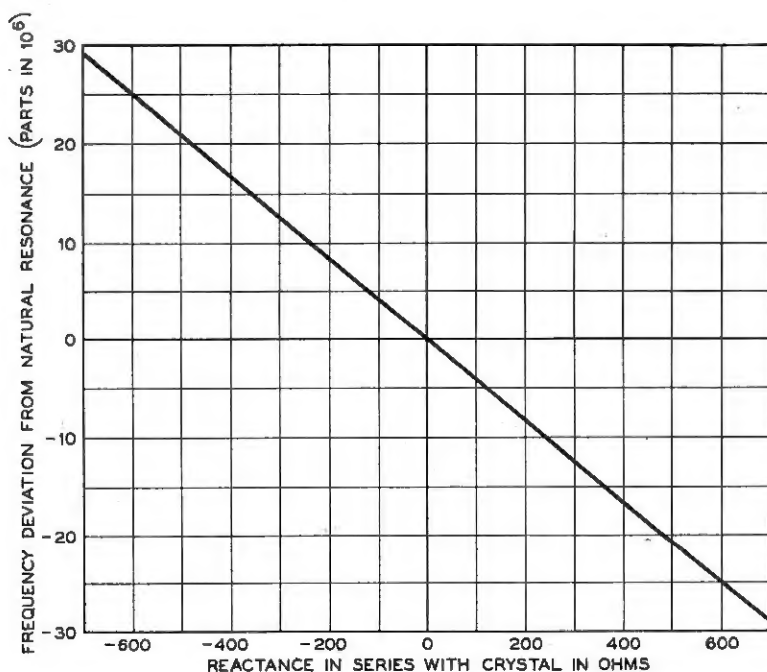


Fig. 10—Frequency of oscillator vs. adjusting reactance.

were obtained over a period of several months. Figure 11 is a photograph of a section of this record. It shows the short-time variations of both oscillators plus a small amount of scattering caused by the measuring equipment itself. The crystals were temperature-controlled in separate ovens, and the power was supplied from separate sets of laboratory batteries controlled to about ± 2 per cent in voltage. Shielding was ample to avoid any tendency to lock in step.

In addition to these small short-time variations, the oscillators exhibited a very slow upward drift in frequency, attributed to aging

of the mounted crystals. This aging decreased in a regular manner with time, the mean drift of one of the crystals being less than one part in ten million per month after three months of continuous operation,

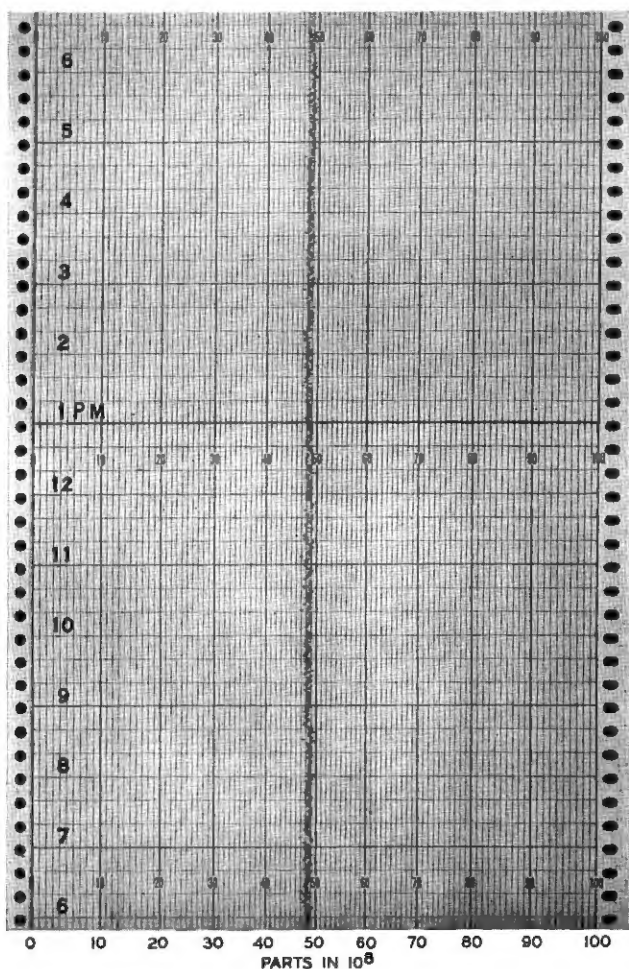


Fig. 11—Record of frequency comparison between two bridge stabilized oscillators. Full scale one part in a million. Variations less than ± 2 parts in one hundred million.

and about a third of this amount after seven months. In most applications, gradual frequency drift is not objectionable even though the required accuracy is very high, for readjustment is merely a matter of setting a calibrated dial.

APPLICATION

The bridge stabilized oscillator promises to become a useful tool in many commercial fields as well as in certain purely scientific problems such as time determination and physical and astronomical measurement. It may be used either to increase the frequency precision in applications where operating conditions are accurately controlled, or else to make such control unnecessary, affording high stability in spite of unfavorable conditions.

An interesting application in the field of geophysics has already been made in the form of a "Crystal Chronometer." This chronometer consists of a single-tube bridge oscillator, a frequency dividing circuit, and a synchronous timing motor. It was recently loaned by Bell Telephone Laboratories to the American Geophysical Union and was used with the Meinesz gravity-measuring equipment on a submarine gravity-survey expedition in the West Indies. Although operating under somewhat adverse conditions of power supply, temperature, and vibration, it was reported⁶ to be more stable than any timing device previously available, errors in the gravity measurements introduced by the chronometer being negligibly small.

⁶ "Gravity Measurement on the U. S. S. Barracuda," M. Ewing, and "Crystal Chronometer Time in Gravity Surveys," A. J. Hoskinson; pp. 66 and 77 resp., *Transactions of the American Geophysical Union*, Part I, 1937.